

Reprinted from the JOURNAL OF EXPERIMENTAL PSYCHOLOGY,
Vol. 21, No. 6, December, 1937
Printed in U. S. A.

A STUDY OF DIFFERENTIAL PITCH SENSITIVITY
RELATIVE TO AUDITORY THEORY



A STUDY OF DIFFERENTIAL PITCH SENSITIVITY RELATIVE TO AUDITORY THEORY ¹

BY CHARLES CLEMENT IRWIN

University of Michigan

According to interpretations of the Wever-Bray effect, the auditory mechanism functions primarily for the conduction of sound waves to the auditory nerve, which transmits them unaltered in pattern to the cerebral hemispheres. Thus, tonal analysis in the cochlea may or may not be present. Ruckmick, (1) in his latest review of the field of audition, cautions against a too-close correspondence between physiological determinants, such as Wever and Bray obtained, and psychological data; he is among those who conclude that mental auditory sensation can not be assumed to follow directly from electrical acoustical effects.

The experiments by Culler, Finch, and Girden (2) with trained dogs led them to the conclusion that tests of hearing are the only reliable basis for the interpretation of a given physiological phenomenon. Merely because such phenomena have been observed in connection with the auditory mechanism does not warrant an inference for its actual acoustic value.

Recently, studies on the pathology of tone deafness in humans (3) and the relationship of physiological phenomena (in animals) to auditory stimuli (4, 5) have presented direct evidence for tone localization in the cochlea. The correspondence of frequency-localization on the basilar membrane, however, is not specific, and for the region of low tones the evidence is meager. These studies make it increasingly apparent that, in such an intricate hydrodynamic structure as the cochlea, selective response can not be explained merely by principles of sympathetic resonance. It has been the

¹ Part of a dissertation presented in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

purpose of the present investigation² to obtain precise information regarding pitch sensitivity at a single frequency level which could be used as a factor in an explanation of auditory nerve excitation and conduction. Pitch thresholds were determined under the following conditions: (1) Supraliminal, medium, and loud sensation levels; (2) Loudness inequality of the tonal stimuli; (3) Time intervals of 1, 10, 30, and 60 seconds between members of paired stimuli of equal loudness; (4) Time intervals of 1, 10, and 30 seconds between members of paired stimuli of unequal loudness.

Thus it was proposed that changes in experimental technique would produce corresponding changes in acuity for pitch which could be interpreted as evidence of the mechanism for frequency analysis. The chief emphasis has been to develop a rigorous technique for the production and reception of as nearly a pure, constant stimulus as the present status of the physical sciences would permit, and to obtain information for pitch thresholds at the frequency level of 256 cycles per second.

Perhaps the most difficult phase of any problem in physiological acoustics is the production of a suitable stimulus. It is indeed a paradox that, surrounded as we are by a veritable universe of vibrating motion, the ideal sound for experimental purposes does not exist naturally. Purity of tone, characterized by a single frequency and steady loudness, together with variability of tone-pitch and loudness are the requisites to be sought for in an auditory stimulus but which have been attained only in part. Helmholtz proved conclusively that most instruments generate tones which are very complex and are characterized by the given pitch predominating over the component ones. Thus, even the simplest tone occurs as a "pitch-blend" and depends upon the relative strengths of the partial pitches which make it up. While the harmonics constitute the greatest source of impurity, the methods of activation and cessation of the tone introduce disturbing factors which are with difficulty eliminated. Consequently, of the several types of sound generators possible, only a few

² Professor Carl R. Brown supervised the study and designed the apparatus.

are capable of producing a tone suitable for physiological acoustics.

During the past two decades there has been an increasing tendency in physiological acoustics to utilize the principles of vibrating plates and diaphragms for sound generators. Wien (6) and Guernsey (7), in their work on liminal sound intensities in 1903 and 1922 respectively, were apparently among the first investigators to use an audion oscillating circuit and telephone receivers in a psychological study. As early as 1894, however, the physicist Rayleigh (8) employed this type of generator to determine threshold intensities for frequencies up to 768 d.v.

In 1931, Shower and Biddulph (9), employing heterodyne oscillators, modulators, and amplifiers, together with specially constructed receivers, determined pitch sensitivity at various frequencies and loudness levels. Electrical filters of the band-pass type were employed 'to eliminate the harmonics due to the non-linearity of the oscillator and amplifier circuits, and the extraneous sounds introduced by the power supply.' Acoustic wave filters to insure purity of output from the receivers, however, were not included in the apparatus.

Recently, Snow (10), using an elaborate electrical sound generator similar to that employed by Shower and Biddulph, has studied the effect of loudness upon pitch at frequencies from 75 to 1,000 cycles per second. Although the louder of two tones was usually judged to have the lower pitch, Snow obtained wide variations in the results for different observers and for the same observer on different occasions. The greatest shift in pitch was for the frequency of 100 cycles per second; its apparent pitch was lowered by as much as 50 percent for extreme loudness levels. Very little change in pitch was found at 1,000 cycles per second.

APPARATUS

The sound generators used in the present investigation were mechanically activated tuning forks. The frequency of the constant pitch fork was 256 dv/sec; that of the variable pitch fork was some 32 dv/sec higher. By placing different U-shaped pieces of brass over the ends of the prongs of the variable fork, its frequency was made to differ from the constant pitch fork by gradations of 0.25 dv/sec up to 2 dv/sec, and

by gradations of 0.5 dv/sec from 2 to 7 dv/sec. These frequency differences were timed by the method of counting beats.

Each tuning fork was placed in a separate double-walled box, the outside surface of the inner wall and the inside surface of the outer wall being covered with thick hair felt. Between the two walls was a four-inch dead air space. These precautions were necessary to avoid undue dissipation of the energy of the forks and to exclude noises from the environment.

From each sound box extended a brass pipe of three-eighths inch inside diameter; these tubes conducted the sound to an adjoining sound-proof room where the observations were made. Provision for equating the loudness of the forks was made in these tubes by the insertion of brass plates containing holes of various diameters. Inside the sound-proof room, the tones passed through an acoustic filter, and at proper intervals were allowed to continue through a six-inch air valve to the ear of the observer. A three-cushion head rest enabled the subject to hold his ear comfortably and in a fixed position against the end of the sound tube. The tuning forks were controlled electrically by a motor driven timer.

Developed as an analogue of the electric wave filter, the acoustic filter provides for the attenuation of certain vibration frequencies and allows for the passage of a restricted range. Since any disturbing frequencies that might accompany the fundamental of the tuning fork would be harmonics, these undesired bands would lie outside the fundamental band and hence could be separated by filtering action. This would not be possible if the entire frequency group fell within a single band. The acoustic wave filter used in the present investigation is the simplest of the band-pass type. With the side branches open, it passes frequencies lying within the upper and lower limits of the band and attenuates all others. With the side branches closed, the filter becomes a low-pass filter—passing frequencies from zero up to a given cut-off frequency. As the limits of the frequency bands vary inversely as the square root of the volume of the chambers, the locations of the pass-bands may be shifted by varying the volume of the filter.

In addition to the attenuation of undesirable frequencies, the band-pass filter with its quick change to the low-pass type serves as a convenient device for varying the sensation level of tones. Thus, with the pass-band of frequencies set just above the fundamental of the tone presented, the fundamental frequency will be attenuated as well as its harmonics. With the same setting of the filter volume, but acting as a low-pass type, the fundamental frequency is transmitted but the harmonics are attenuated as in the band-pass filter.

PROCEDURE

The method of right and wrong cases, or constant stimuli, was employed in every phase of the procedure. Curves, based upon data obtained for stimulus differences above and below the apparent threshold, were interpolated to give the true threshold at 75 per cent correct judgments. The number of trials varied with the observer and the several parts of the investigation. For the determination of pitch sensitivity at different loudness levels, the number of trials per observer ranged from 250 to well over 3,000. For the study of the effect of unequal loudness of the two tones, and also of the longer time intervals between the presentations of the tones, the trials were fewer.

Ordinarily the tones were presented for a duration of one second separated by an interval of one second; the pairs of stimuli were given every ten seconds for a series of twenty-five trials. The order of presentation of high and low tones was predeter-

mined by a key which allowed for an equal number of H and L and no more than two trials of the same order in succession. The observer judged the second tone of each pair to be either higher or lower than the first; where the subject was doubtful, he was required to guess. The judgments were signalled by means of a buzzer to the experimenter in an adjacent room.

Preliminary to any determination of pitch sensitivity the stimuli were equated for loudness. This was accomplished by first making the tuning forks of identical frequency; and, second, by giving a series of twenty-five trials. If the subject reported 50 percent correct judgments (chance), the stimuli were assumed to be of equal loudness. Usually the subject based his judgment upon pitch rather than upon loudness differences—the second tone always appearing higher to some observers and lower to others. Throughout the investigation, the forks were maintained at a constant intensity level, the loudness being just above the threshold when the acoustic filter was of the band-pass type. Different sensation levels were obtained by changing the action of the filter from the band-pass to the low-pass type.

SUBJECTS

With two exceptions, the subjects were students in the elementary psychology courses. Most of them had little or no musical training; they all had, apparently, normal hearing. In addition to these students, the services of two students working under the National Youth Administration program were obtained. With these latter subjects, it was possible to obtain a large amount of data. Serving as observers daily for a period of several months, their judgments on pitch discrimination at various loudness levels totalled over 6000. One of these subjects was a highly trained musician, having a pitch limen of a quarter of a vibration per second. Limens were obtained for twelve subjects for two or more experimental conditions.

Part I. Variation of Loudness Level

In this part of the investigation, limens were determined principally at two intensity levels: supra-liminal and the full intensity of the tuning fork. In each case, the supra-liminal tones were just above the intensity threshold (this varied slightly for the several subjects), and the full intensity tones approximated in intensity level 50–60 decibels. In a given experimental session, series of 25 trials were alternated for the loud and for the weak tones. Thus, in successive test periods the sequence of presentation of the several series was varied to eliminate any conditioning effect of a given loudness level upon the one following it.

Part II. The Effect of Loudness upon Pitch

In Part I, both members of the pair of stimuli were of equal loudness; the tones were presented at a low, at a medium, and again at a relatively high loudness level. This procedure was designed to measure pitch sensitivity for various degrees of excitation of the auditory mechanism. The purpose of Part II was to show the effect upon pitch of varying the loudness of one member of the pair of stimuli while the second member was held at a constant loudness level. Thus, while the procedure of Part I attempted to measure the effect of loudness upon pitch discrimination, that of Part II attempted to measure the effect of loudness upon the attribute of pitch, *per se*.

The procedure adopted to show the effect of decrease in intensity upon pitch was as follows: Since a decrease in loudness was judged to be an increase in pitch, the lower frequency tone was always made weaker, regardless of whether it was presented

first or second. The frequency of the higher tone was then increased until it was judged to be equal in pitch to the low-weak tone. The loudness level of the variable frequency tone was held constant at 50-60 db; that of the standard frequency tone (256 dv/sec) was decreased by 15 percent.

Part III. Variation of Time Interval between the Members of Paired Stimuli

In Part I and Part II, the tones were presented for a duration of one second separated by an interval of one second; successive pairs were presented every ten seconds. For the longer time intervals between the members of a given pair, periods of ten, thirty, and sixty seconds were chosen. Corresponding intervals of ten, thirty, and sixty seconds were allowed between the presentations of successive pairs. Manual control of the sound valve in the sound-proof room provided for the audibility of either the higher or the lower frequency tone at the proper time.

Perhaps the most rigorous test of the effect of time interval upon pitch discrimination is the variation of the time interval during a given series of judgments. Thus, following the presentation of, say, a dozen pairs of one second interval tones, a group of ten second interval tones would be given; then the interval would be successively increased to the thirty second, and even a few of the sixty second interval pairs would be presented during a single series.

The subject would then be given a rest period, the air in the sound-proof room changed, and another series beginning with the longer intervals and ending with the one-second interval would be given. The observers often reported that they were not conscious of any change in the length of the time interval which exceeded ten seconds. This fact would indicate an ideal experimental condition, relative both to technique and to the attitude of the observer.

Part IV. The Effect of Loudness upon Pitch with Variation in Time Interval

The procedure here was simply a combination of that in Part II and Part III.

RESULTS

The limens for pitch have been tabulated for each subject for the several experimental conditions. For Part I Variation of Loudness Level and Part III Variation of Time Interval, the changes in the limens as effected by a variation in the experimental condition are shown.

Part I.—All the observers agreed that the only difference in judging the tones at the different loudness levels was in the greater degree of attention required for the supra-liminal tones. In most cases, daily variation in pitch sensitivity was slight. Although the determinations extended over a period of several months, there was no evidence of practice effect.

Part II.—When the stimulus difference was small, all of the observers were perfectly confident that the louder tone was lower in pitch than the weaker tone. This was shown conclusively when the tones were equated for frequency, but

TABLE I

Subjects	Ric	Bru	Par	Cox	Ste	All	Gei	Con	Mye	Lon	Lea	Sne
PART I												
Supra-Liminal . .	0.28	1.45	1.60	1.64	1.55	1.42	3.80					
Full	0.25	1.50	1.65	1.55	1.45	1.50	2.90	1.50	2.10	2.00	1.15	1.55
Medium	0.28	1.65										
PART II—UNEQUAL LOUDNESS												
	1.52	10.00	2.80		3.10	1.80		4.40	2.00	3.90		
PART III												
10 Seconds	0.35	1.20	0.90		1.50	0.80		1.25	1.50	1.45	0.65	0.95
30 Seconds	0.40							1.40	1.40	1.55		
60 Seconds	0.55							1.10	2.10	1.40		
PART IV—UNEQUAL LOUDNESS												
10 Seconds	1.10							4.60	1.60	4.30		
30 Seconds	1.00							5.40	1.00	4.50		

The above values are limens for pitch discrimination expressed as that difference in frequency (dv/sec) to which the observer would respond correctly in 75 percent of his judgments (Parts I and III); and in 50 percent of his judgments (Parts II and IV).

The limens were interpolated from curves.

TABLE II

Subjects	Ric	Bru	Par	Cox	Ste	All	Gei	Con	Mye	Lon	Lea	Sne
Part I. Decrease in Loudness Level to Supra-Liminal—												
+	0.03			0.09	0.10		0.90					
—		0.05	0.05			0.08						
Part III. Increase of Time Interval to:												
10 seconds +	0.10				0.05							
—		0.25	0.75			0.70		0.25	0.60	0.55	0.50	0.60
30 seconds +	0.15											
—								0.10	0.70	0.45		
60 seconds +	0.30											
—								0.40	0.00	0.60		

The above values represent the changes in the limens (dv/sec) effected by a variation of the experimental conditions. The change is relative to the limen obtained for the given standard condition: stimuli of equal loudness (50–60 db) presented for duration of 1 second with time interval of 1 second between members of pair. An increase in the limen is indicated by (+), a decrease by (—).

one was presented as slightly louder than the other. As the difference in loudness was increased, there was a corresponding increase in the percent of judgments indicating the louder tone to be lower in pitch.

Part III.—For the comparison of the 10 second with the 1 second time interval between members of the paired stimuli, limens were determined for ten subjects; limens for the 30 and the 60 second intervals were obtained with four of these observers. In eight of the ten cases there was a decrease in the limen with an increase in the interval from 1 to 10 seconds.

The majority of observers reported that stimuli separated by an interval of 10 seconds were much easier to judge than those separated by only 1 second. Judgments for the 30 second interval were similar to those for the 10 second period. Judgments for the longer intervals were often made relative to the first member only of the pair of tones. Thus, after hearing one of the tones, the observer could predict the pitch of the second before hearing it. Usually these predictions were not changed by the appearance of the second tone. Whether the prediction actually proved to be correct or not seemed to depend only upon the magnitude of the stimulus difference.

Part IV.—When both the factors of loudness inequality and variation of time interval are present, the result is an increase in the limen for some observers and a decrease for others.

SUMMARY OF RESULTS

1. For the frequency level of 256 cycles per second, differential pitch sensitivity remains constant for supra-liminal, medium intensity, and loud tones.

2. Daily variation in acuity is slight; there is no evidence of practice effect in pitch discrimination for ears of very acute or of average sensitivity.

3. For the loudness level of 50–60 decibels, a moderate decrease in intensity produces a relatively great increase in pitch.

4. Pitch sensitivity increases with the lengthening of the time interval between members of the stimuli pair from 1 to

10 seconds. There is a smaller increase in sensitivity for the time intervals of 30 and of 60 seconds.

5. The influence of loudness upon pitch becomes more effective for some observers and less effective for others with an increase in time interval.

INTERPRETATION OF RESULTS

If the modernized resonance theory of hearing is accepted, then the fact that differential pitch sensitivity remains constant for supra-liminal, medium intensity, and loud tones means simply that the same nerve fibers respond to these different degrees of stimulation with equal readiness for the analysis of pitch. Assuming that the intensity of the tones is correlated with the frequency of impulses in these particular fibers, then loudness may vary while pitch sensitivity remains constant. If, however, loudness is correlated with the number of fibers activated, as required by the principles of resonance, then there should be a greater spread of neural response for loud tones than for supraliminal tones and pitch discrimination should be affected.

Wever and Bray, in an explanation of their study of action currents generated in the auditory nerve, make both frequency and intensity dependent upon the frequency of nerve impulses per unit time. While this view does not explain the mechanism for hearing, it permits both multiplicity of fibers and frequency of impulse to contribute toward the total number of impulses in the auditory nerve which is correlated with pitch and loudness. Upon the basis of the present results, it is proposed that when a given magnitude of neural response is exceeded, spatial mechanical resonance becomes inadequate as a basis for pitch discrimination and is supplemented (wholly or in part) by frequency of impulse.

The results of the second part of the investigation, the variation of pitch with loudness, offer further modifications for a 'place theory' of pitch based upon principles of resonance. In the majority of cases, there is a definite rise in pitch corresponding to a decrease in intensity of stimulation. With respect to the resonant properties of the organ of Corti, this

means a shift in response toward the basal end of the cochlea. Such a change in location would indicate that pitch is correlated with certain asymmetrical properties of the auditory mechanism which cause a variation in the pattern of response with different degrees of stimulation of the membrane-partition.

When we consider auditory experience as correlated with the total number of impulses in the auditory nerve, the variation of pitch with loudness presents evidence which is somewhat contradictory. Assuming that the total number of impulses passing along the nerve per unit time is correlated with both pitch and loudness, then a decrease in either of these factors is a decrease in the total number of impulses. But this summation of impulses appears to be something more than a simple addition or subtraction process. The decrease in stimulus intensity does not merely reduce the number of those impulses specific for intensity and hence produce a decrease in the loudness of the sensation. A secondary effect is produced upon pitch, and where the reduction in intensity is moderate this secondary effect of rise in pitch predominates over the primary effect of decrease in loudness.

If the attribute pitch were independent of the attribute loudness and remained constant irrespective of intensity changes, then it could be argued that pitch had its own set of impulses and loudness had its set and the increase or decrease in the total number of impulses caused by either of the factors would not affect the other. The interdependence of the attributes, however, raises a serious objection to the acceptance of a volley theory of pitch and intensity. Thus, while the results of the first part of the study tended to show the inadequacy of a simple resonance mechanism for frequency analysis, the change of pitch with loudness, as evidenced in the second part, seems to discredit the notion of pitch and loudness as dependent primarily upon a summation effect of nerve impulses.

That the ultimate analysis of frequency may depend upon the co-functioning of the central nervous system finds sup-

porting evidence in the results of the third and the fourth part of the study. Thus the increase in pitch sensitivity and the shift in the loudness effect upon pitch with the lengthening of the time interval may indicate that the central processes function more effectively when a sensation of pitch is allowed to "sink in" than when it is immediately followed by a dissimilar sensation.

(Manuscript received July 13, 1937)

REFERENCES

1. RUCKNICK, C. A., A critical review of the field of audition, *Psychol. Bull.*, 1936, 33, 407.
2. CULLER, E. A., FINCH, G. AND GIRDEN, E., Functions of the round window in hearing, *Amer. J. Physiol.*, 1935, 111, 416-425.
3. CROWE, S. J., GUILD, S. R. AND POLVOGT, L. M., Observations on the pathology of high-tone deafness, *Bull. Johns Hosp.*, 1934-35, 54, 315-340.
4. STEVENS, S. S. AND DAVIS, H., Psychophysiological acoustics: pitch and loudness, *J. Acoust. Soc.*, 1936, 8, 1.
5. DAVIS, H., DERBYSHIRE, H. J., LURIE, M. H., KEMP, E. H. AND UPTON, M., Functional and histological changes in the cochlea of the guinea pig resulting from prolonged stimulation, *J. Gen. Psych.*, 1935, 12, 251-278.
6. WIEN, Über die Empfindlichkeit des menschlichen Ohres für Töne verschiedener Röhre, *Pflüger's Arch.*, 1903, 97, 1.
7. GUERNSEY, M., Study of liminal sound intensities, *Amer. J. Psych.*, 1922, 33, 554.
8. RAYLEIGH, On the minimum audible current in the telephone, *Phil. Mag.*, 1894, 38, 285-295.
9. SHOWER, E. G. AND BIDDULPH, R., Differential pitch sensitivity, *J. Acoust. Soc.*, Oct. 1931.
10. SNOW, W. B., Change of pitch with loudness at low frequencies, *J. Acoust. Soc.*, 1936, 8, 14.